MULTI-STAGE FLUX-TRAPPING HELICAL FLUX COMPRESSION GENERATORS*

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Abstract

Several types of multi-stage flux-trapping helical flux compression generators for high impedance loads are considered. Short-pulse two-stage helical generators with diameter 100 mm and initial energy of 0.5-3 kJ have supplied energy up to 40 kJ into a 5-μH inductive load in a time of about 15 μs. Long-pulse two-stage generators with final helix diameter of 110 mm initial energy of 0.8-2.7 kJ have supplied energy up to 350 kJ into a 0.3-μH inductive load. Long-pulse three-stage generators with final helix diameter of 160 mm and initial energy of approximately 5 kJ have supplied up to 700 kJ into a 0.5-μH inductive load. Model generators without flux trapping and with final helix diameter of 160 mm and initial energy of approximately 20 kJ have supplied energy up to 1.0 MJ into a 0.5-μH inductive load. Long-pulse two-stage generators with final helix diameter of 160 mm and initial energy of approximately 30 kJ produce energy up to 1.6 MJ in a load of 0.5 μH.

I. INTRODUCTION

Today, high power sources of electrical impulses are widely used to solve problems in modern high energy density physics. Among single-pulse generators, explosively driven systems seem to be the most attractive, because they are rather simple, compact, and cheap constructions, which have very high specific characteristics and adequate reliability. Actually, it is well known that high explosives (HE) store a large amount of chemical energy—up to 10 MJ/kg; this is approximately 5-6 orders of magnitude higher than that of capacitors. To convert chemical energy from HE into electromagnetic pulse energy for specific devices, so-called magnetocumulative generators (MCG) have designed [1-3]. The principle of MCG action is based on the effect of magnetic accumulation during compression of magnetic flux by a metal conductor pushed by HE detonation products. One of the typical and simplest constructions consists of a helical coil wrapped around a copper cylinder filled with HE. Permanent magnets, piezoceramics, or small capacitors supply an initial current of few hundred amperes that creates an initial magnetic field in the gap between the coil and cylinder. The explosion compresses the magnetic field and drives it into the load, where a very short-duration powerful electrical impulse is created. Actually, energy levels in loads as high as 100 MJ, currents as high as 300 MA, and voltages as high as 1 MV have been achieved with specific energy of 100 KJ/cc and specific power of 10 MW/cc. Peak energies and powers for special types of MCGs are estimated to be as high as 1 GJ and 100 TW [2].

The aim of this paper is to describe experiments with the several types of MCGs with flux trapping to produce electrical impulses into high impedance loads.

II. ESTIMATION OF MCG MAIN PARAMETERS

To analyze experiments with MCGs and to estimate their main features, it is necessary to rewrite the well known relations for MCG performance. In the simplest one-loop equivalent electrical circuit, the MCG inductance is simulated by a time-decreasing function $L_g(t)$ and the load by a constant inductance L_n. Resistance $R(t)$ formally includes all losses of magnetic flux. For any time t one can obtain [3]:

$$LI = L_0 I_0 \exp\left\{-\int_0^t \frac{R}{L}\,dt\right\} = L_0 I_0 \varphi(t), \qquad \textbf{(1)}$$

where I_0 is the current and L_0 is the total inductance at time $t=0$ and $\varphi(t)$ is the coefficient of flux conservation. For current and energy increase in the circuit we find the following expressions:

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14. ABSTRACT
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$$I/I_0 = \lambda\varphi\,, \quad \textbf{(2)}$$

$$\psi = E/E_0 = \lambda\varphi^2\,, \quad \textbf{(3)}$$

where $\lambda = L_0/L$ is the inductance reduction coefficient.

For flux trapping systems it is convenient to rewrite the main relations through the final current I_{2k} and coefficient of magnetic flux amplification ϕ^* in the lossless circuit [4]:

$$I_{2k}^* = \left(k_{120} - k_{130}k_{230}\right)\frac{\sqrt{L_1 L_{20}}}{L_n} I_{10}\,; \quad \textbf{(4)}$$

$$\phi^* = \frac{\left(k_{120} - k_{130}k_{230}\right)}{\left(1 - k_{130}^2\right)}\sqrt{\frac{L_{20}}{L_1}}\,. \quad \textbf{(5)}$$

Here, L_1 and L_{20} are inductances of the outer and inner solenoids, I_{10} is the initial current in the outer coil, and k_{ij} are coupling coefficients. The relations for the actual current and energy amplification will be [4]:

$$I_{2k} = I_{2k}^*\varphi = \frac{\left(k_{120} - k_{130}k_{230}\right)^2}{\left(1 - k_{130}^2\right)\phi^*} I_{10}\lambda\varphi\,; \quad \textbf{(6)}$$

$$\psi = \frac{\left(k_{120} - k_{130}k_{230}\right)^2}{\left(1 - k_{130}^2\right)}\lambda\varphi^2\,. \quad \textbf{(7)}$$

These formulas are sufficient for estimating the main parameters of the MCG for desired output parameters. To get good MCG performance it is necessary to minimize magnetic flux losses due to breakdowns and to avoid ohmic heating of the wires. The most dangerous electrical breakdowns are expected to be between the moving armature and the MCG coil. If the helix length is much more that that of the expanding armature cone the E.M.F. in the circuit may be estimated as $\varepsilon = I_2 dL_2/dt + I_1 dMdt$ (the last term is for an MCG with flux trapping). For MCGs with flux trapping it is very important to understand the voltage of the open circuit before the generator starts to work: $U_{oc} \cong \phi^* L_1 dI_1/dt$. In the MCGs described below these voltages reached values as high as 100-150 kV, so that they required special precautions to avoid breakdowns.

To diminish voltages we use the exponential law of inductance output [5]. To estimate minimal possible pitch, h_m, and cross section of the wires, S_{min}, that will prevent severe ohmic heating of the helix wires, we've used the integral of action criterion [3]. In Fig.1, curves 1a - 1c represent the necessary winding pitches to provide an exponential law of output inductance for helix diameters of 6, 10, and 20 cm, respectively. Curves 2a and 2 b are calculated for a capacitor bank and flux trapping suppliers, for the case of current flowing through the whole cross section of the wire. Curves 3a and 3b are the same, but with current flowing only through within a skin depth. It is seen that only the largest coil diameter can provide the necessary MCG parameters.

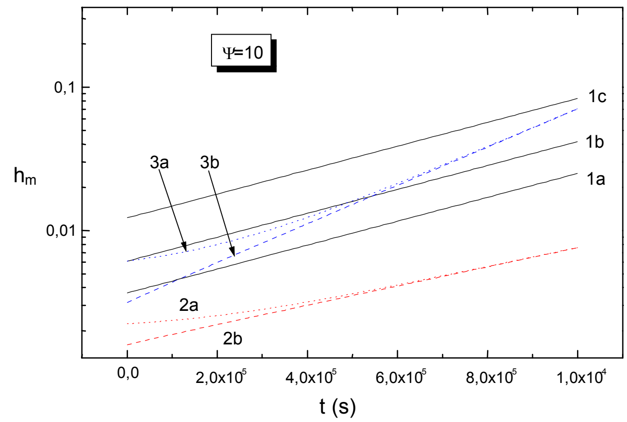

Figure 1. Helix pitch time dependence for $\psi = 10$ and $E_k = 1.6$ MJ.

III. EXPERIMENTAL RESULTS

Several types of multi-stage flux-trapping helical flux compression generators were tested.

A. Short-Pulse Two-Stage MCG

The scheme of the short-pulse two-stage generator is presented in Fig. 2. The MCG consists of a helical "booster" generator with inductance L_2 that is used for amplification of the initial magnetic energy and a flux-trapping generator with an inner solenoid L_3, outer solenoid L_{2H}, which is necessary to obtain short electrical pulses in the load L_H. The initial current in solenoid L_2 is supplied by a capacitor bank discharge. When the secondary circuit is switched in, magnetic flux is trapped and pushed out into the L_3 load. The "booster" stage has a diameter of 100 mm and length of 260-480 mm. The cylindrical second MCG stage has length 80 mm, outer diameter 100 mm and a pitch 2.5 mm. The copper armature has an outer diameter of 50 mm and a wall thickness of 2 mm. The mass of HE is approximately 1 kg.

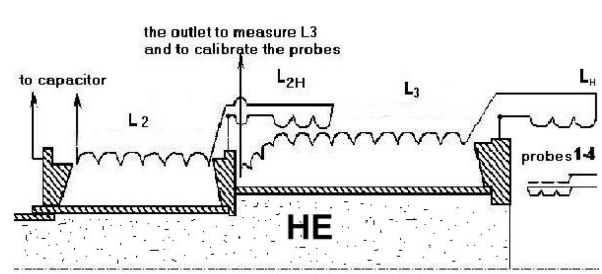

Figure 2. Scheme of the two-stage MCG.

The designed two-cascade MCG with initial energy of 0.5-3 kJ produces an electrical pulse of 25-40 kJ into an inductive load L_H = 5 μH in a time of approximately 15 μs. Some typical results of the experimental investigations are presented in Table 1.

Table 1. Short-pulse two-stage MCG parameters.

Exp. N	*1*	*2*	*3*	*4*
L_2, μH	**218**	**222.9**	**206.3**	**279.5**
L_{2H}, μH	**0.4**	**0.4**	**0.46**	**0.13**
L_3, μH	**38.4**	**55.5**	**40.2**	**33.55**
L_H,μH	**5.1**	**5.78**	**5.2**	**5.24**
I_0, kA	**2.49**	**2.16**	**8.3**	**15.6**
E_0, kJ	**0.68**	**0.52**	**1.3**	**3.4**
I_B, kA	**347.3**	**306.5**	**349.0**	**832**
I_3, kA	**97.0**	**89.1**	**112.0**	**122.9**
E_3, kJ	**24.0**	**22.9**	**32.5**	**39.5**
$\psi_{1,3}$	**35.5**	**44.1**	**25**	**11.6**

B. Long-Pulse Two-Stage MCG

The first cascade, or "booster" generator, was made with a helix diameter of 74 mm and liner diameter of 30 mm. The length of the "booster" generator was not more than 500 mm. The output inductance function of the "booster" generator was chosen so that the current derivative and the spiral voltage did not exceed 30 kA/μs and 70 kV, respectively. The length of the second stage was about 530 mm and diameter of the helix was 110 mm. The outer solenoid was wound only over the first two sections of the second stage and had a length of 200 mm. The transformation coefficient was $\phi \sim$ 10-12, and it allowed us to limit the open-circuit voltage to 90 kV. Total mass of HE of this MCG does not exceed 1.5 kg. Typical results of the experiments are in shown in Table 2.

C. Long-Pulse Three-Stage Generator

The scheme of the three-stage MCG is shown in Fig. 3. The "booster" generator with a length of 500 mm energizes the second stage generator, with length of 500 mm, by magnetic flux trapping. Both stages were constructed with the same helix diameter of 110 mm, the same diameter of copper liner, 50 mm, and they were connected by a crowbar. The third stage has a diameter of 160 mm, length of 600-800 mm, and liner diameter of 70 mm. The first two stages and the third one were ignited separately at corresponding times. The total mass of HE was 4.5 kg. A photograph of the three-stage MCG is presented in Fig. 4.

Table 2. Long-pulse two-stage MCG parameters.

Exp. N	**1**	**2**	**3**
L_2, μH	**81**	**80**	**80**
L_{2H}, μH	**0.26**	**0.22**	**0.26**
L_3, μH	**40.7**	**60.4**	**60.1**
L_H, μH	**0.31**	**0.3**	**0.28**
W_0, kJ	**0.8**	**2.75**	**1.50**
W_{2H}, kJ	**105**	**101**	**93**
W_H, kJ	**255**	**251**	**350**
φ	**0.28**	**0.16**	**0.22**
ψ	**318**	**91**	**230**

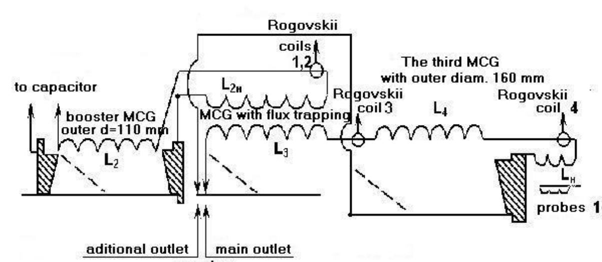

Figure 3. Scheme of the three-stage MCG.

Typical results of the experiments with the three-stage MCG are presented in Table 3 (Columns 1 and 2). Using an initial energy of approximately 5 kJ, it has supplied energy up to 700 kJ into a 0.5-μH inductive load. Total energy amplification was as high as 220 in these tests.

D. Model MCG with 160 mm Output Diameter

To examine processes at megajoule energies, we have investigated a model MCG without flux trapping. This generator was composed of two parts: the first part was made with a diameter of 110 mm and had a 50-mm liner

diameter; the second part consisted of a helix of 160 mm diameter and a liner diameter of 70 mm. A conical section placed in the second part allowed a smooth transition between helix diameters. The angle of the cone was 34^0. The total mass of HE was 4.5 kg. Typical parameters of this experiment are indicated in Table 3 (Column 3). With an initial energy of 26.6 kJ, this MCG supplied 1 MJ of energy into a 0.5-μH inductive load.

Figure 4. View of the three-stage MCG before test.

Table 3. Three-stage MCG parameters.

Exp. N	1	2	3	4	5
L_2, μH	**84,7**	**84,9**	**300**	**30,8**	**31,67**
$L_{2н}$, μH	**0,39**	**0,3**	**--**	**0,14**	**0,2**
L_3, μH	**121,8**	**114**	**--**	**--**	**--**
L_4, μH	**34,05**	**27,0**	**22,3**	**30,67**	**42,6**
$L_н$, μH	**0,53**	**0,54**	**0,50**	**0,49**	**0,49**
W_0, kJ	**4,2**	**2,3**	**26,6**	**16**	**29,6**
$W_{2н}$, kJ	**236**	**104**	**--**	**380**	**434**
$W_н$, kJ	**661**	**500**	**1000**	**840**	**1590**
$I_н$, kA	**1580**	**1360**	**2000**	**1820**	**2552**
φ	**0,4**	**0,52**	**0,49**	**0,46**	**0,54**
ψ	**157**	**217**	**37**	**42**	**54**

E. Long-Pulse Two-Stage Generators

The scheme of this MCG is similar to that of that described in paragraph ***C***. However, liners with diameters of 50mm and 70 mm were joined by a conical section and HE with a mass of 4.5 kg was initiated only from one point. The flux-trapping section was designed over the cone and partially over the 160-mm-diameter helix. With initial energy of approximately 30 kJ this MCG produced up to 1.6 MJ in a 0.5-μH load. Typical parameters of the experiments are shown in Table 3 (Columns 4 and 5) and oscilloscope traces of load current and current derivative from experiment number 4 are presented in Fig. 5.

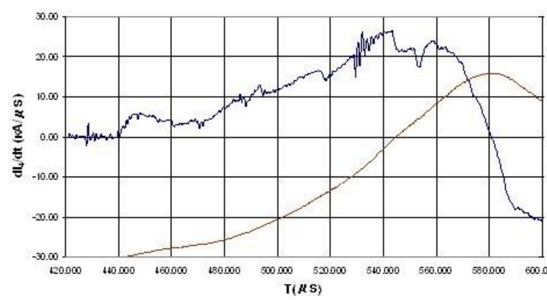

Figure 5. Oscilloscope traces of current derivative and current in the 0.5-μH load (Experiment No. 4).

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